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A review on distributed energy resources and MicroGrid

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Abstract

The distributed energy resources (DER) comprise several technologies, such as diesel engines, micro turbines, fuel cells, photovoltaic, small wind turbines, etc. The coordinated operation and control of DER together with controllable loads and storage devices, such as flywheels, energy capacitors and batteries are central to the concept of MicroGrid (MG). MG can operate interconnected to the main distribution grid, or in an islanded mode. This paper reviews the researches and studies on MG technology. The operation of MG and the MG in the market environment are also described in the paper.

Keywords: Distributed energy resources (DER); MicroGrid (MG); Operation; Multi-agent system (MAS)

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1. Introduction

Due to the technology development and environment protection, some distributed energy resources (DER), such as internal combustion (IC) engines, gas turbines, microturbines, photovoltaic, fuel cells and wind-power [1], have emerged within the distribution system. However, application of individual distributed generators can cause as many problems as it may solve. A better way to realize the emerging potential of distributed generation and associated loads is a subsystem called "MicroGrid" (MG).

In [2], the MG concept assumes a cluster of loads and MicroSources (MS) operating as a single controllable system that provides both power and heat to its local area. Refs. [2,3] introduce the benefits of MG, such as, enhance local reliability, reduce feeder losses, support local voltages, provide increased efficiency through using waste heat combined heat and power (CHP), voltage sag correction or provide uninterruptible power supply functions.

The MG is intended to operate in the following two different operating conditions: normal interconnected mode and emergency mode (islanded mode) [4]. Most DERs that can be installed in an MG are not suitable for direct connection to the electrical network due to the characteristics of the energy produced. Therefore, power electronic interfaces (dc/ac or ac/dc/ac) are required. Inverter control is thus the main concern in MG operation.

The MG is centrally controlled and managed by a MG central controller (MGCC) installed at the medium voltage/low voltage (MV/LV) substation. The MGCC includes several key functions, such as economic managing functions and control functionalities, and is the head of the hierarchical control systems [4].

The aim of this paper is to review the researches and studies on MG technology. In Section 2, it will introduce some current situations about MG, especially in Europe and Japan. In Section 3, MG architecture is described, including MS, storage devices, and inverters. In Section 4, two approaches in the MG emergency operation is discussed in details. Also the fault detection and safely analysis is included in this section. Last section introduces the MG in the market environment. Multi-agent system (MAS) is proposed to be the main technique in this section.

2. Current situations about MG

"MICROGRIDS" project is part of the European Research Project Cluster "Integration of RES + DG (distributed generation)" projects. It will investigate, develop and

demonstrate the operation, control, protection, safety and telecommunication infrastructure of MG and will determine and quantify their economic benefits. This project aims at the increase of penetration of micro-generation in electrical networks through the exploitation and extension of the MG concept, involving the investigation of alternative microgenerator control strategies and alternative network designs, development of new tools for multi-MG management operation and standardization of technical and commercial protocols. More information can be obtained from [5].

Amorim et al. [6] presents a brief characterization, to a Portuguese LV grid, developed in MICROGRIDS project. This project is being developed in Frielas, which is a residential zone, supplied by a LV feeder from a public distribution power station of 200 kVA. The paper focuses some improvements in terms of efficiency and reliability. It gives several conclusions. The control and protection hardware must be upgraded to allow the supplying of the customers in island mode; the transition from grid-connected mode to island mode should be analyzed carefully in order to prevent voltage disturbances in the MG; the MG black-start is other important challenge. Some tests have demonstrated the incapacity of the microturbine to support the transient peak demand of a typical distribution MV/LV transformer during its initial magnetization.

In Japan, the New Energy and Industrial Technology Development Organization (NEDO) started three research projects, which deal with new energy integration to local power system field test in 2004 [7]. The sites are in Aomori, Aichi and Kyoto. In Aomori project, field tests were started to develop a distributed energy supply system, in which some loads in special districts are supplied by this supply system with private power lines and makes no influence to utility power system with which the energy supply system is connected at one point. In Aichi project, fuel cells are used as main generations.

Besides the ordinary ac-grid (alternating current) system, [8] proposes a *dc-grid* (*direct current*) *system* having distribution power generators. It has designed and constructed an experimental system based on a 10 kW dc having a solar-cell generator unit, a wind turbine generator unit, an electric power storage unit, power-leveling unit, and an ac-grid connected inverter unit. Experiment results show that there are no circulating current flows among the units. An appropriate amount of the generated power is cooperatively allotted to both the ac grid inverter unit and the storage unit with output impedance characteristics.

3. MG architecture

In a basic MG architecture (Fig. 1), the electrical system is assumed to be radial with several feeders and a collection of loads. The radial system is connected to the distribution system through a separation device, usually a static switch, called point of common coupling (PCC). Each feeder has circuit breaker and power flow controller.

Developed within the EU R&D MG project, the MG concept adopted in this research involves an operational architecture (Fig. 2). It comprises an LV network, loads (some of them interruptible), both controllable and non-controllable MS, storage devices, and a hierarchical-type management and control scheme supported by a communication infrastructure used to monitor and control MS and loads.

The head of the hierarchical control system is the MGCC. At a second hierarchical control level, load controllers (LC) and microsource controller (MC) exchange

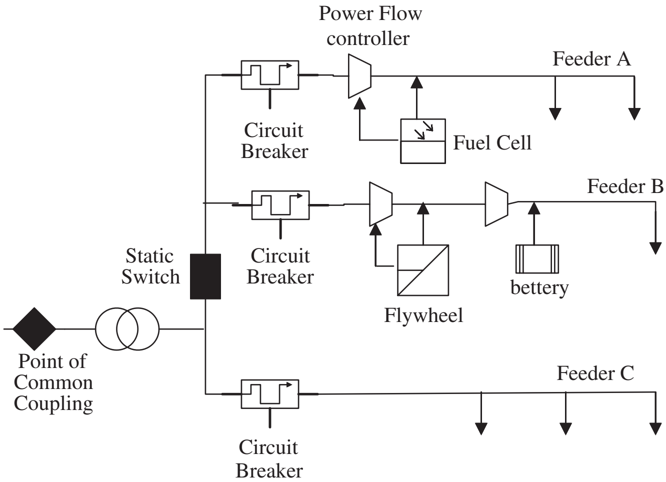


Fig. 1. Basic MG architecture.

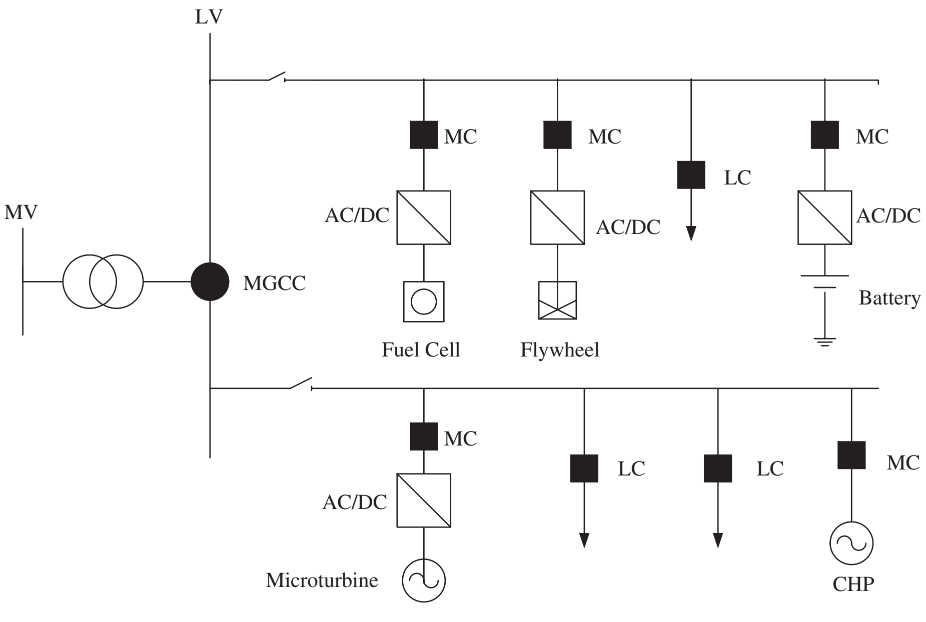


Fig. 2. MG architecture with MGCC.

information with the MGCC that manages MG operation by providing set-points to both LC and MC.

The amount of data to be exchanged between network controllers is small, since it includes mainly messages containing set-points to LC and MC, information requests sent by the MGCC to LC and MC about active and reactive powers, and voltage levels and messages to control MG switches.

3.1. MicroSources

The MS of special interest for MGs are small (<100 kW) units with power electronic interfaces. These sources, including microturbines, wind generators, photovoltaic arrays, PV panels and fuel cells, are placed at customers sites. They are low cost, low voltage and have high reliable with few emission.

Despite this impressive list of benefits, [9] points out that DER penetration have not met expectations. Major drawbacks to increased DER utilization are high cost, the need for custom engineering, lack of plug and play integration methods and few successful business models. Many private and public organizations are aggressively addressing these drawbacks, including the Department of Energy and state organization.

In [1], some emerging generation technologies are introduced in details. Several MS models, able to describe their dynamic behavior, have been developed in [10]. Also in [11], a simple combination control method for different kinds of DER to compensate load demand fluctuation in a MG is proposed.

3.2. Storage devices

The current power systems (can named as MacroGrid) have storage provided through the generators inertia. When a new load comes on line, the initial energy balance is satisfied by the system's inertia. This results in a slight reduction in system frequency. Lasseter [2] points out that a system with clusters of MS designed to operate in an island mode must provide some form of storage to insure initial energy balance.

Due to the large time constants (from 10 to 200 s) of the responses of some MS, such as fuel-cells and microturbines, storage devices must be able to provide the amount of power required to balance the system following disturbances and/or significant load changes. These devices act as controllable ac voltage sources to face sudden system changes such as in load-following situations. In spite of acting as voltage sources, these devices have physical limitations and thus a finite capacity for storing energy.

The necessary MG storage can come several forms; batteries or super-capacitors on the dc bus for each MS; direct connection of ac storage devices (batteries, flywheels, etc.); or use of traditional generation with inertia with the MS.

Venkataramanan and Illindala [12] conducts that a lead–acid battery is considered the most suitable for MG applications. They are capable of providing large currents for a very short interval of time.

3.3. Inverter controller

Most MS technologies that can be installed in an MG are not suitable for direct connection to the electrical network due to the characteristics of the energy produced. Therefore, power electronic interfaces (dc/ac or ac/dc/ac) are required (Fig. 3). Inverter control is thus the main concern in MG operation.

Pecas Lopes et al. [4] introduces two kinds of control strategies used to operate an inverter. The inverter model is derived according to the following control strategies. PQ inverter control: the inverter is used to supply a given active and reactive power set point. Voltage source inverter (VSI) control: the inverter is controlled to "feed" the load with pre-defined values for voltage and frequency.

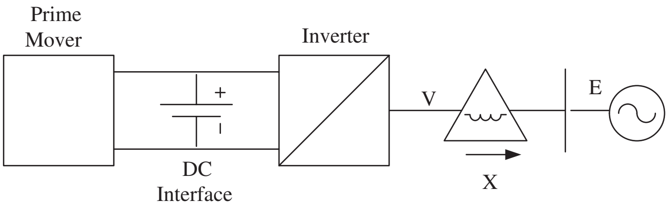


Fig. 3. Interface inverter system.

In [1], operation of the MG assumes that the power electronic controls of current MS are modified to provide a set of key functions. The critical system performance components are the voltage versus reactive power droop and power versus frequency droop.

Voltage vs. reactive power (Q) droop

Voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of MS could experience voltage and/or reactive power oscillations. With small errors in voltage set points, the circulating current can exceed the ratings of the MS. This situation requires a voltage vs. reactive power droop controller so that, as the reactive power generated by the MS becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage set point is increased.

Power vs. frequency droop

In island mode, problems from slight errors in frequency generation at each inverter and the need to change power-operating points to match load changes need be addressed. Power vs. frequency droop functions at each MS can effectively solve these problems without a communication network. When the MG separates from the grid, the voltage phase angle at each MS has a change, resulting in an apparent reduction in local frequency. This frequency reduction coupled with a power increase allows for each MS to provide its proportional share of power.

Li et al. [13] presents the design and analysis of a controller for multi-bus MG system. The controller proposed for use with each distributed generation (DG) system in the MG contains inner voltage and current loops for regulating the three-phase grid-interfacing inverter, and external power control loops for controlling real and reactive power flow and for facilitating power sharing between the paralleled DG systems when a utility fault occurs and the MG islands.

Li et al. [14] proposes a grid-interfacing power quality compensator using two inverters (inverters A and B) to control both the sensitive lead voltages in the MG and the line currents flowing between the MG and utility system. The main functions of shunt inverter A are to maintain a balanced set of sensitive load voltages in the MG under all grid and load operating conditions, while the main functions of series inverter B are to inject appropriate voltage components along the distribution feeder to balance the line currents and to limit the flow of large fault currents during utility voltage sags.

4. Emergency operation, fault detection, and safety analysis of MG

MG flexibility can be achieved by allowing its operation under two different conditions. One is normal interconnected mode, in which the MG is connected to a main MV grid

being either partially supplied from it or injecting some amount of power into it. The other is emergency mode, in which the MG operates autonomously (as in physical islands) when the disconnection from the upstream MV network occurs.

The MG islanding process may result from an intentional disconnection from the MV grid (due to maintenance needs) or from a forced disconnection (due to a fault in the MV network).

4.1. Two approaches in emergency operation of MG

Pes Lopes et al. [15] describes two approaches to deal with MG islanded operation. In the first approach, the main concern is related to inverter control modes. As the MG is an inverter-dominated grid, frequency and voltage control during islanded operation is performed through inverters. The other approach closely follows concepts related to conventional synchronous machine control.

A. *MG operation regarding inverters control modes*
If a cluster of MS is operated within a MG and the main power supply (the MV network) is available, all the inverters can be operated in PQ mode, because there are voltage and frequency references. However, a VSI can be used to provide a reference for frequency and it will be possible to operate the MG in islanded mode and to smoothly move to islanded operation without changing the control mode of any inverter. The combination of primary frequency regulation provided by storage devices, load-shedding schemes for less important loads and secondary load frequency control are the key for successful MG islanded operation. More details and specific information can be obtained from [12]. It gives the details of inverter internal control and relative simulations.

B. *MG operation regarding primary energy source control*
In this representation, the MS and storage device can be represented by synchronous generators or by STATCOM battery energy storage (STATCOM-BES). In grid-connected mode, the frequency of the MG is maintained within a tight range. However, following a disturbance, the frequency of the MG may change rapidly due to the low inertia present in the MG. The control of the MS and storage devices is very important in order to maintain the frequency of the MG during islanded operation (see [4,12]). With droop control action, a load change in the MG will result in steady-state frequency and voltage deviations, depending on the droop characteristics and frequency/voltage sensitivity of the load. The storage device will contribute to the overall change in generation. Restoration of the frequency/voltage of the MG to their normal values requires a supplementary secondary frequency control action to adjust automatically the output of the storage device.

4.2. Fault detection in MG

When the MG is operating as a self-contained power island, any fault current will have to be supplied by those generators still connected to it. These fault currents may have relatively low values. The difficulty caused by using generation that relies on converters is that these units are designed to limit their output current to protect their power devices. Typically this limit is set to about twice their rated output current (see [2,16]). This is

insufficient to trip conventional over-current protection and therefore other protection techniques have to be found.

Lasseter [2] concludes that the unique nature of the MG design and operation requires a fresh look into the fundamentals of relaying. One approach that is quite powerful is to develop a real-time fault location technique that will identify the exact location of the fault much more accurately that the classical relaying is capable of doing under any circumstances. These methods may prove too costly. Low cost approach such a current transformer (CT) based zero sequence detection, and differential current and/or voltage methods also show promise.

Hernandez-Gonzalez and Iravani [16] presents an active islanding detection technique for a DR unit at the distribution voltage level, which uses a three-phase, voltage-sourced converter (VSC) as the interface unit. The proposed method is based on injecting a disturbance signal into the system through either the direct axis (*d*-axis) or the quadrate axis (*q*-axis) current controllers of the interface voltage-sourced converter. Signal injection through the d-axis controller modulates the amplitude of the voltage at the PCC, whereas signal injection through the *q*-axis controller causes a frequency deviation at PCC, under islanded conditions.

AI-Nasseri et al. [17] introduces a new type of protection scheme which is able to protect against faults that are both internal and external to a set zone of protection scheme, based on the abc-dq transformation for the voltage waveforms is able to identify the presence of a short circuit fault and to facilitate discrimination between faults which are either inside or outside a set zone of the MG.

Mahinda Vilathgamuwa et al. [18] presents the resistance–inductance (RL) feedforward and flux-charge model feedback algorithms for protecting utility-interfaced MG from large line currents during utility-voltage sags. The RL algorithm functions by controlling a series inverter, connected between the micro and utility grids, to insert large virtual RL impedance along the distribution feeder to limit the line currents and damp transient oscillations with a finite amount of active power circulating through the series (and shunt) inverter.

4.3. Safely analysis of MG

A fault in a MG may generate substantial ground potential rise, even if the energy sources operate at LV. Thus grounding of the distributed energy sources and the transformer connecting the MG to the utility network must be carefully analyzed and appropriate rules need to be developed.

LV earthing systems are defined according to the earthing techniques of the secondary of the MV/LV transformer (supply source) and the frame of the load equipment. LV neutral earthing is broadly categorized in to three types: TT, IT and TN (see [19]). The TN-C-S is the first choice for MG earthing and the second choice would be TT. Besides, a grounding system for a typical MG has been designed in [19] and its adequacy during fault conditions studied from an electrical safety point of view. The safety criterion of touch voltage and the step voltage has been adopted.

In [20], a method of small-signal stability analysis of power systems with MG is proposed. The small-signal stability of the system can be evaluated by computing the eigenvalues of the dynamic equations around the operating steady state point.

5. MG in market environment

5.1. MG using a multi-agent system (MAS)

The use of MAS technology can solve a number of specific operational problems. First of all, small DER units have different owners, and several decisions should be taken locally so centralized control is difficult. Furthermore MGs operate in a liberalized market; therefore the decisions of the controller of each unit concerning the market should have a certain degree of "intelligence". Finally the local DER units besides selling power to the network have also other task: producing heat for local installations, keeping the voltage locally at a certain level or providing a backup system for local critical loads in case of a failure of the main system (see [21–23]). These tasks suggest the importance of the distributed control and autonomous operation.

Dimeas and Hatziargyriou [21] describes four kinds of agents: production agent, consumption agent, power system agent and MGCC agent. The MGCC agent has only coordinating tasks and more specifically it announces the beginning and the end of a negotiation for a specific period and records final power exchanges between the agents in every period. In the market environment, three control levels are distinguished.

- distribution network operator (DNO) and market operator (MO) at the level of the MV;
- MGCC;
- local controllers (LC), which could be either micro source controllers or load controllers.

The main interface between the DNS/MO and the MG is the MGCC. The MGCC is the main responsible for the optimization of the MG operation, or alternatively, it simply coordinates the LC, which assume the main responsibility for this optimization. Ref. [22] describes the main functions required by the MGCC for the efficient MG participation in future real-time markets following different policies.

5.2. An operational cycle of the MG

Dimeas and Hatziargyriou [23] presents an operational cycle of the system in the market environment.

- The MGCC announces the beginning of the market period.
- The power sellers estimate their actual production capabilities and generate the proper number of power-seller market agents.
- The loads estimate their actual demands and generate the proper number of power buyer market agents.
- The power system agent, depending on the number of the seller and buyer agents, generates sufficient number of agents, in order to make the system symmetrical. Next, it calculates the total number N of the sellers (or buyers) and generates an extra set of N sellers and N buyers. This allows a production unit to sell directly to the grid or gives the ability to a lead to buy directly from the grid.
- The MGCC announces the start of the new negotiation cycle.
- The energy market sellers and buyers agents bid in the market, according to some algorithm.

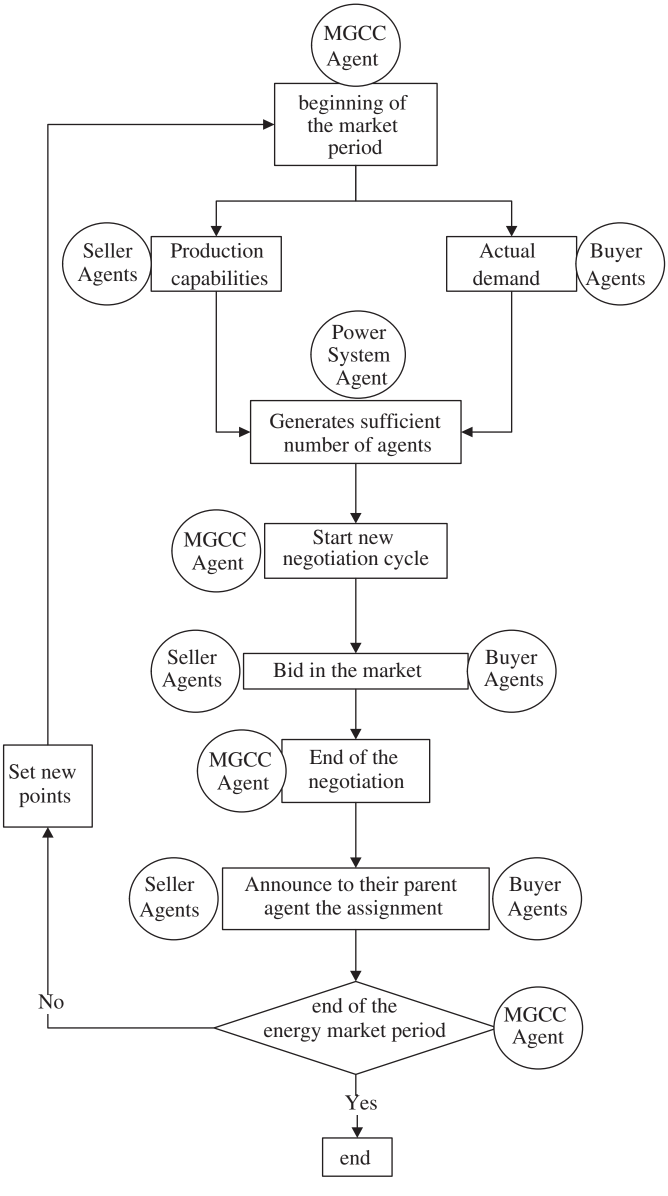


Fig. 4. Agents operational cycle.

- The MGCC announces the end of the current negotiation.
- The sellers and buyers agents announce to their parent agent their assignment and then terminate themselves.
- The MGCC announces the end of the energy market period.
- The MGCC announces the new set points.

Fig. 4 shows the agent operational cycle of the MG.

5.3. Optimal solution of MG

Alibhai et al. [24] introduces four major auction types used in MG. They are first-price sealed bid, Vickrey, English and Dutch. In this paper, it presented techniques and simulation results for coordinating energy loads and sources in a single community within a MG. Under conditions without a large number of loads and sources, the choice of an auction type depends on whether total messages or price has higher importance. When there are a large number of loads and sources, Dutch auctions are preferable.

In [25], the paper presents a rational method of building MGs optimized for cost and subject to reliability constraints. The method is based on dynamic programming and consists of determining the optimal interconnection between MS and lead points, given their locations and the rights of way for possible interconnections.

In [26], an algorithm able to deal with the reconfiguration of distribution system is proposed in order to find the optimal combination of MGs. In the search of the best configuration among different combinations of MGs, the algorithm uses a Sequential Monte Carlo simulation technique. The final structure found by the algorithm maximizes the sum of the savings in both the cost of energy purchasing and the cost of service interruptions.

In [27], the paper is focused on the development of a novel energy management system (EMS) based on the application of neural networks (NN). The EMS is able to autonomously make decisions and determine hour-by-hour the correct dispatch of generators with the final goal of minimizing the global energy costs. The application of the EMS to a small test case has showed significant saves in the global energy bill by using typical Italian energy and fuel price data.

6. Conclusion

This paper makes a conclusion on the works and researches that make efforts on DER and MG. It introduces the current situations about MG and MG architecture. Furthermore, the operation in a MG is described in details. At last, the MG in market environment is also concluded in the paper.

MG is a new type of power system. The technique is still not mature nowadays. A lot of works have to be done until it can be put in the market. Japan and some Europe organization have put some efforts into it, although it is still under the research and experimental stage.

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